BBC RD 1977/23

1 9 7 4
THE QUEEN'S AWARD
TO INDUSTRY

RESEARCH DEPARTMENT

REPORT

METAL-HALIDE DISCHARGE LAMPS: the measurement of intensity ripple and a note on operation at high supply frequencies

E.W. Taylor, M.A.(Cantab.), C.Eng., M.I.E.E.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION June 1977

BBC RD 1977/23
UDC 621.327
621.391.837.3
621.3.08

METAL-HALIDE DISCHARGE LAMPS: THE MEASUREMENT OF INTENSITY RIPPLE AND A NOTE ON OPERATION AT HIGH SUPPLY FREQUENCIES

E.W. Taylor, M.A.(Cantab.), C.Eng., M.I.E.E.

Summary

Details of the equipment used to measure the variations of light intensity ("intensity ripple") from metal-halide discharge lamps are discussed, and an estimate of the accuracy of the ripple ratio values derived from the measurements is given. The assessment of the "safe" lamp supply frequency, above which the effects of intensity ripple on film exposure may be discounted, is discussed in the Appendix.

Issued under the authority of

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

June 1977

(PH-177)

METAL-HALIDE DISCHARGE LAMPS: THE MEASUREMENT OF INTENSITY RIPPLE AND A NOTE ON OPERATION AT HIGH SUPPLY FREQUENCIES

Section | Title | Page

Summary .... Title Page

1. Introduction 1

2. Lamp ballasting 1

  2.1. General 1
  2.2. Resistive ballast 1
  2.3. Reactive ballast 2

3. The measurement of power dissipated in the lamp 2

4. Experimental details 4

  4.1. Equipment arrangement 4
  4.2. Overall spectral response 5

5. Estimate of accuracy of ripple measurement 5

6. Conclusions 6

7. References 6

APPENDIX: Safe lamp operating techniques 7

METAL-HALIDE DISCHARGE LAMPS: THE MEASUREMENT OF INTENSITY RIPPLE AND A NOTE ON OPERATION AT HIGH SUPPLY FREQUENCIES

E.W. Taylor, M.A.(Cantab.), C.Eng., M.I.E.E.

1. Introduction

Previous reports[1,2,3,4] have outlined the use of metal-halide discharge lamps as light sources in motion-picture filming, and have discussed the effects on film exposure of the alternating "ripple" component of light intensity which occurs at twice the supply frequency. This present report discusses the practical details involved in making measurements of this ripple component. Up to the present time the work has been principally concerned with the use of sinusoidal power supply sources of differing frequency, but the same method of measurement can in principle be applied to any type of lamp excitation (e.g. a supply providing a "square" current waveform so that the current through the lamp is constant in magnitude but periodically reverses in direction).

The relationship between the frequency of a sinusoidal lamp power source and the resulting intensity ripple magnitude can be found using the techniques described in this Report. This relationship may be used to determine the minimum lamp supply frequency, above which the possibility of film exposure variations may be discounted. A method of finding this "safe" lamp supply frequency is given in the Appendix to this Report.

2. Lamp ballasting

2.1. General

In common with all other forms of discharge lamp, metal-halide lamps must be supplied from a power source of finite impedance, sufficient to offset the negative-resistance characteristic of the lamp itself. This is usually[5a,5b,6a] achieved by incorporating an impedance or "ballast" of suitable value (resistive or reactive) in series with the lamp.* In the present case the lamps under test were provided by the manufacturers with inductive ballast units for use on conventional 240-volt 50 Hz supplies. Sections 2.2. and 2.3. below describe ballast arrangements for use on supplies of differing frequency or non-sinusoidal waveform.

2.2. Resistive ballast

The simplest form of ballast is a resistance[5a] placed in series with the lamp. The minimum value of this resistance is determined by two factors. In the first place, it must be sufficient to offset the negative-resistance characteristic of the lamp. In addition, it must be remembered that the lamp current falls to zero every half cycle of the alternating supply. A certain minimum voltage is required to re-initiate the current flow through the lamp and the voltage applied across the combination of lamp and ballast must be sufficient to ensure that this re-initiation of current flow takes place. The value of ballast resistance is then set by the need to control the power dissipated in the lamp to the nominal rated value when this "re-ignition" voltage is applied to the lamp circuit. In practice the second of these two factors determines the minimum ballast resistance value. A further complication arises from the fact that the re-ignition voltage is higher when the lamp is started from cold than when it has reached its final operating temperature. The minimum ballast resistance value, required to limit the lamp dissipation to safe values when starting, is therefore greater than the value required when the lamp is warm. Fig. 1 shows the resistive ballasting arrangement that was adopted to avoid excessive power loss in the ballast resistance.* The resistance was reduced by closing switch S_1 once the lamp had warmed up, while the input supply voltage (V_{in} in Fig. 1) was adjusted to suit starting or running conditions using the variable autotransformer T_1. The values of resistors R_1 and R_2 were chosen to suit the particular lamp under test: for a particular lamp with a rated power dissipation of 575w, for example, R_1 was 5·6 ohms and dissipated 320 watts when the lamp was run at its rated power, while R_2 was 9·1 ohms and dissipated 530 watts under these conditions.

Lamp current waveform was monitored by observing the voltage (V_{IL}) across the low resistance R_3. When testing lamps of high power rating this resistance was water-cooled in order to prevent a significant change in

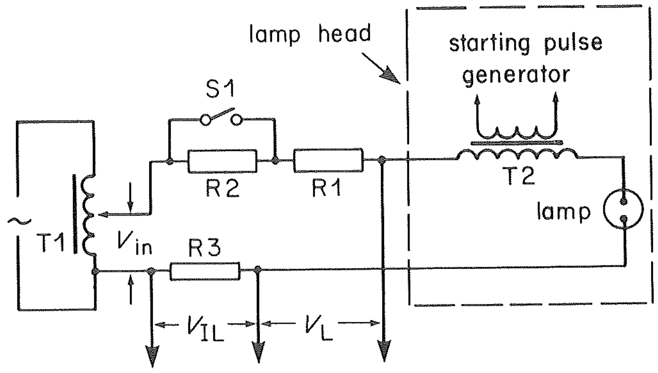


Fig. 1 - Resistive ballasting arrangements

its value. The lamp voltage waveform (V_L) included a component due to the presence of the leads to and from the lamp and the starting transformer T_2 and tests with the lamp replaced by a short-circuit were carried out to evaluate this additional component. From the lamp voltage and current waveforms the power dissipated in the lamp could be calculated (see Section 3). Variations in lamp dissipated power were achieved by adjusting the input supply voltage; after such a change it was important to allow the lamp to achieve stable operation (as detected by constancy of lamp current) before making further measurements of ripple waveform.

---

* It is however possible to design power supplies (for example, battery-operated inverters) having an output impedance suitable for supplying the lamp directly.

* Required since the variable frequency power supply was of limited rating.

Although the loss of power in the ballast resistor was a considerable disadvantage, the use of a resistive ballast had the advantage of independence of lamp supply frequency, enabling the ripple ratio value to be rapidly measured over a wide frequency range (but see Section 2.3.). It was also required in cases where excitation of the lamp by a non-sinusoidal power source was under investigation.

2.3. Reactive ballast

During detailed measurements of ripple ratio, using a sinusoidal power supply source, it was found that the value of the ratio was, perhaps not surprisingly, affected by the waveform of the current passing through the lamp. This waveform was itself influenced, especially at lower supply frequencies, by the type of ballast (e.g. resistive or reactive) and the value of the ballast impedance. Standardized ballasting arrangements were therefore required so that comparable measurements of ripple ratio could be made at different supply frequencies when using sinusoidal lamp supply sources. Since inductive ballasting is almost invariably used when operating from conventional 240v 50 Hz supplies, a similar inductive ballasting arrangement was used (Fig. 2) at higher lamp supply frequencies. The value of the ballast inductance (L, Fig. 2) was adjusted (by varying a gap in the magnetic path of the choke) so that its reactance at the particular supply frequency in use was the same as that of the inductance at 50 Hz.

Since the available power was reduced if the load on the power source was appreciably reactive, a conventional power-factor correction capacitor (C_1 in Fig. 2) was provided to minimize this reactive component as far as possible. The switch S_2 (Fig. 2) was provided to isolate this capacitor from the power supply source until the lamp has been started, since it was found that with some lamps the reactive load presented by this capacitor reduced the available lamp supply voltage to below the value required to strike the lamp.

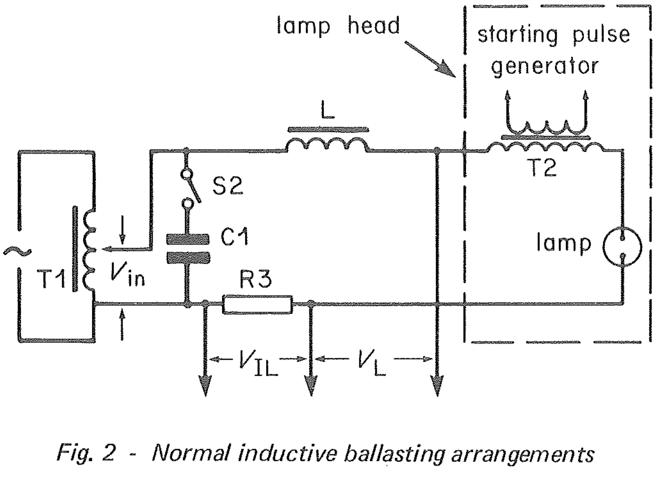


Fig. 2 - Normal inductive ballasting arrangements

At the highest frequency used during the tests (approximately 2 KHz) the leakage inductance of the variable autotransformer became significant. The inductor L was therefore omitted (Fig. 3) and the series capacitor C_2 inserted to adjust the effective ballast impedance to the appropriate value. As before, control of lamp power was obtained by adjusting the ratio of the autotransformer T_1, although in this case such adjustment also altered the effective ballast impedance as well as the voltage supplied to the lamp circuit. At this relatively high supply frequency, however, the effect of ballast impedance on lamp current waveform (and therefore on ripple ratio value) is relatively small and the results obtained in this way are directly comparable to those obtained at lower supply frequencies, using inductive ballasting.

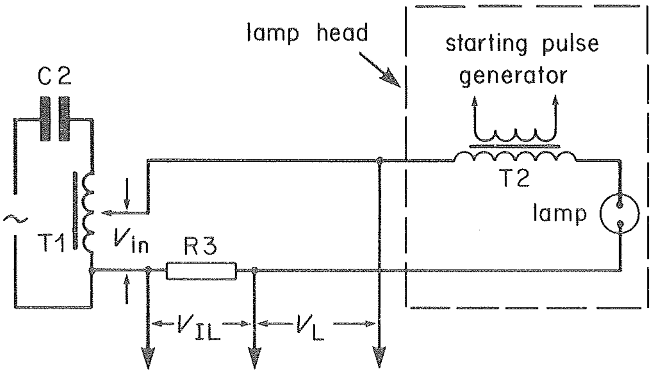


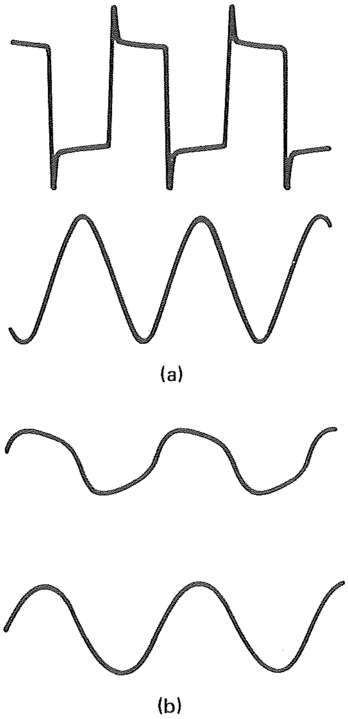
Fig. 3 - Inductive ballasting arrangements for higher supply frequencies

3. The measurement of power dissipated in the lamp

Typical voltage and current waveforms, obtained as described in Section 2, are shown in Fig. 4a and 4b for low (50 Hz) and high (1400 Hz) excitation frequencies, using a sinusoidal supply in each case. It can be seen that while the current waveform was approximately sinusoidal,* the voltage waveform was approximately rectangular in character, especially at the lower frequency. This behaviour is typical of discharge lamps.[5c,6b] If the voltage and current waveforms are taken as strictly rectangular and sinusoidal respectively, alternate half-cycles having peak magnitudes of $\pm V$ and $\pm I_{pk}$, it can be shown that the energy (E) supplied to the lamp in one half

---

* see Section 2.3: at lower supply frequencies the current waveform was markedly non-sinusoidal when using a resistive ballast.



(a)

(b)

Fig. 4 - Typical voltage (upper) and current (lower) waveforms using inductive ballast

(a) Supply frequency 50 Hz
(b) Supply frequency 1400 Hz

The voltage and current scales used at the two supply frequencies are not directly comparable

cycle of the supply is given by

$$E = \frac{\tau}{\pi} V I_{pk}$$

where τ is the period of the supply alternations.

Since this half cycle has a duration of $\tau/2$ the power (W) dissipated by the lamp becomes

$$W = \frac{2}{\pi} V I_{pk}$$

$$= 0{\cdot}637\, V I_{pk} \qquad \ldots\ldots(1a)$$

or, in terms of rms current,

$$W = \frac{2\sqrt{2}}{\pi} V I_{rms}$$

$$= 0{\cdot}9\, V I_{rms} \qquad \ldots\ldots(1b)$$

Equations 1a or 1b can be used to obtain a fairly accurate estimate of the power dissipated in the lamp (say to within about 10%) although an estimate of effective peak voltage has to be made from the practical waveform.

The departures of the voltage and current waveforms from their idealized forms can be more accurately taken into consideration by representing one half-cycle of each waveform as a number (N) of horizontal steps, of equal width and of height equal to the magnitude of the waveform ordinate at the midpoint of the step (Fig. 5). If I_n, v_n represent the heights of the n^{th} current and voltage steps, the dissipated power is then given by

$$W = \frac{\sum_{n=1}^{N} i_n v_n}{N} \qquad \ldots\ldots(2)$$

The accuracy with which the dissipated power is obtained using Equation 2 clearly increases with an increase in the number of steps used to represent the waveforms. In practice it has been found adequate to use ten such steps:

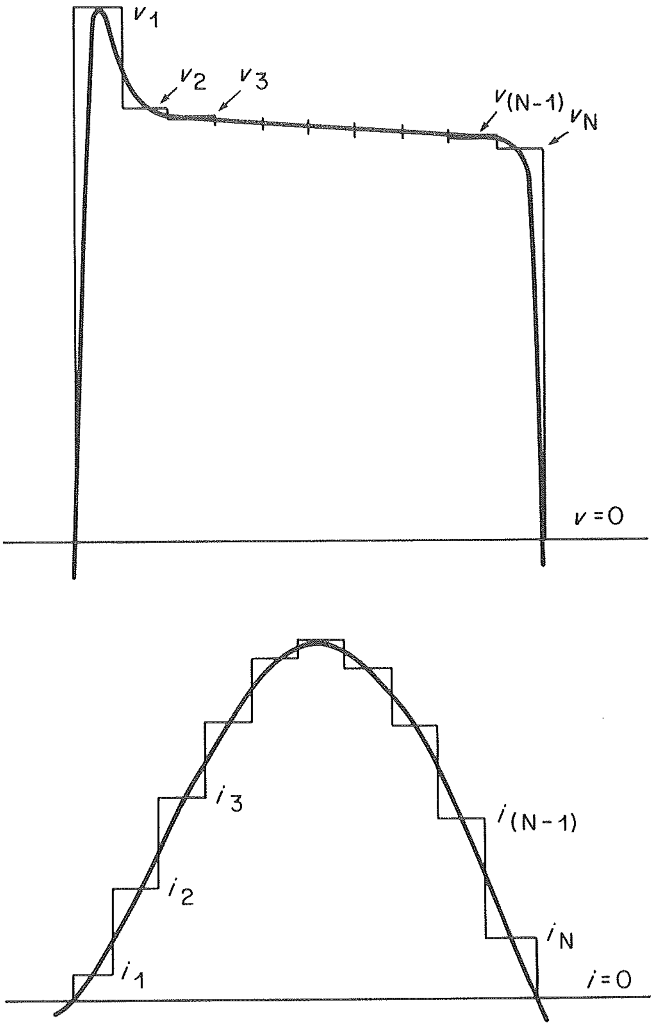


Fig. 5 - Approximations to voltage (upper) and current (lower) waveforms

Thick lines — original waveforms
Thin lines — step approximations

in a trial calculation, the value of dissipated power calculated in this way agreed very closely (within 1%) with the result obtained using fifty steps.

4. Experimental details

4.1. Equipment arrangement

A p-i-n silicon photodiode was used as the photosensitive element. This device acts as a current source and a transresistance amplifier* (current to voltage converter) was used to obtain a suitable output signal. Photodiode illumination was controlled so that a linear relationship between illumination and output signal was always obtained.

A rotating sectored disc in front of the photoreceptor intermittently obscured the photodiode. When the output signal was displayed on a cathode-ray oscilloscope locked to the supply frequency, the signal occurring during these periods of obscuration provided a "zero light" reference against which other levels of illumination could be measured.

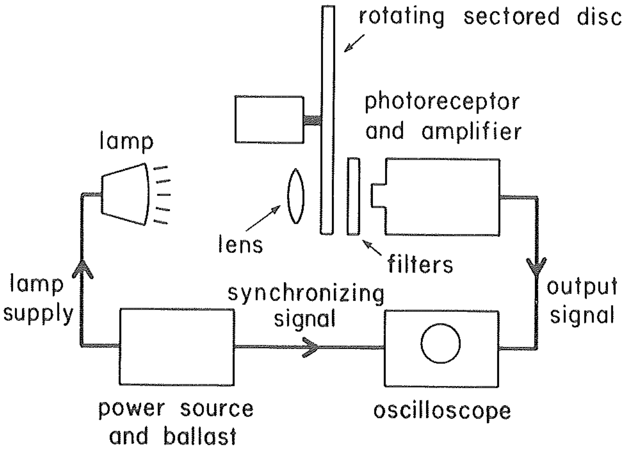


Fig. 6 - Diagram of equipment arrangement (lamp starting circuit not shown)

A diagram of the complete equipment arrangement is shown in Fig. 6 and a general view of the equipment in Fig. 7. The lens was used to increase the photodiode illumination particularly when using the narrow-band colour filters (see Section 4.2.).

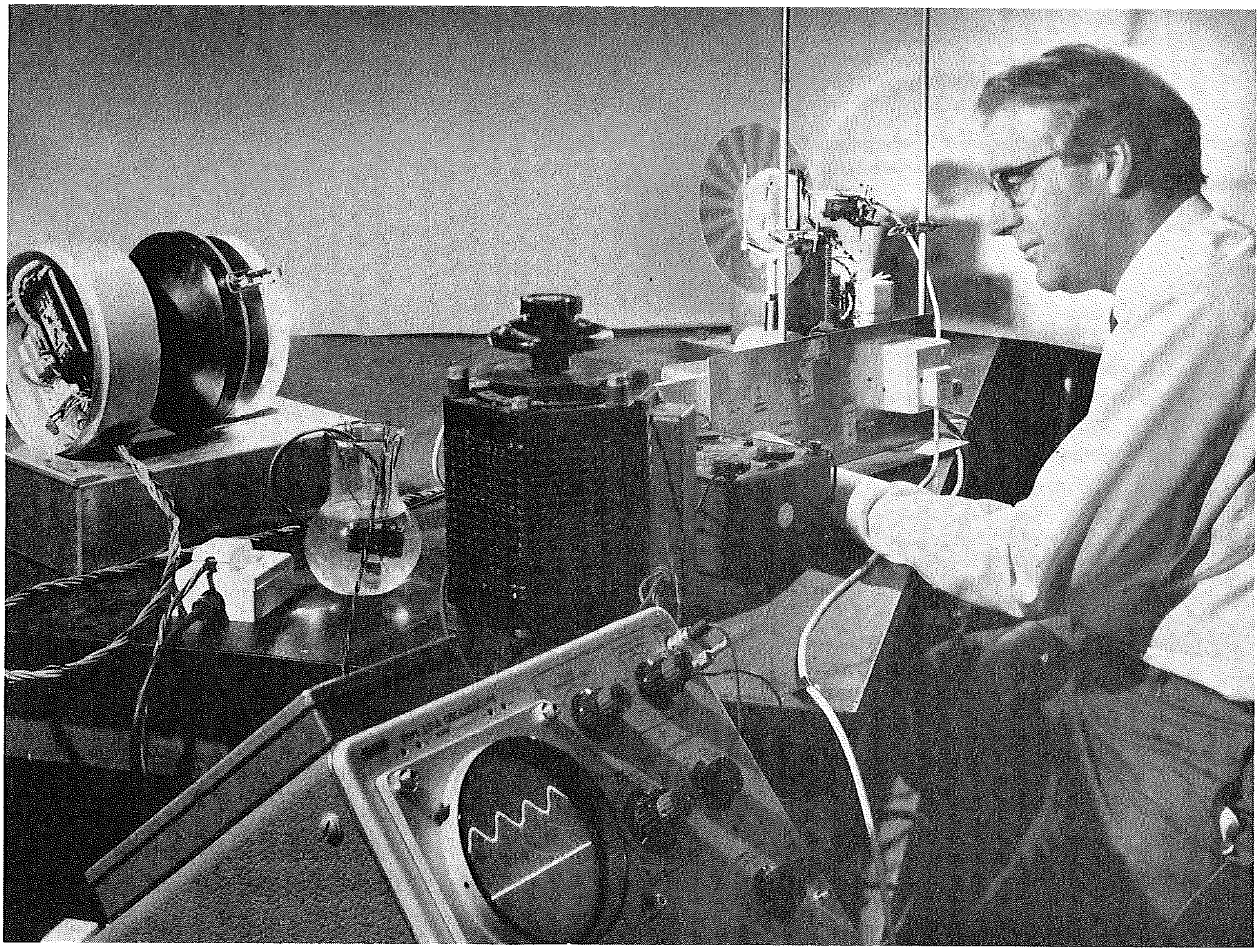


Fig. 7 - View of equipment arrangement

---

* designed by A. Oliphant

4.2. Overall spectral response of photoreceptor

Preliminary measurements of ripple ratio, using narrow-band red, green and blue filters (see below), showed that for some metal-halide lamps the observed value of ripple ratio depended markedly on the particular filter used. It was therefore necessary to control the spectral response of the photoreceptor rather carefully. Since the present investigation related to the use of metal-halide lamps for film lighting applications, a response used in testing cine-camera lenses (Fig. 8, dotted curve) was adopted as appropriate for the broad-band ("white light") photoreceptor response. The chain-dotted curve in Fig. 8 shows the unfiltered photoreceptor response, and the full curve the response achieved in practice. All curves have been normalized to the same maximum value. It can be seen that a considerable shift in peak-response wavelength was required and the sensitivity of the photoreceptor was reduced by a factor of about six when this filtering was applied.

The narrow-band red, green and blue filters mentioned above were intended to represent the spectral sensitivities of the individual layers in a colour film. The responses actually achieved are compared with those of a typical colour film in Fig. 9. An approximate match with the colour film characteristics was achieved, although there were discrepancies in peak wavelength and, in the case of the red characteristic, in width. It is however thought that the results obtained using the narrow-band filters represent reasonably well the effect of light from the lamp under test on the individual layers in a colour film.

5. Estimate of accuracy of ripple measurement

The ripple ratio (p) is defined (ignoring any ripple asymmetry)[3] by the relationship

$$p = \frac{\text{minimum light output}}{\text{maximum light output}} \qquad \ldots\ldots(3)$$

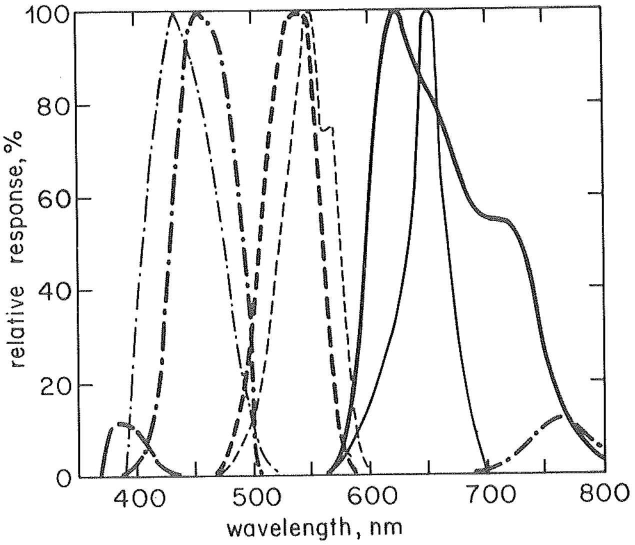


Fig. 9 - Narrow-band spectral responses

——— with red filter
– – – – with green filter
—·— with blue filter

Thick lines – equipment response
Thin lines – colour film response

Errors in reading oscilloscope trace values will clearly result in corresponding errors in ripple ratio value. Typically, the maximum trace height was about 4 cm, while the minimum trace height (after switched attenuator adjustment if necessary) was not less than about 1·6 cm. On this basis it follows that, if the trace height could be read to ±0·5 mm,* then the ripple ratio values were accurate to about ±5%.

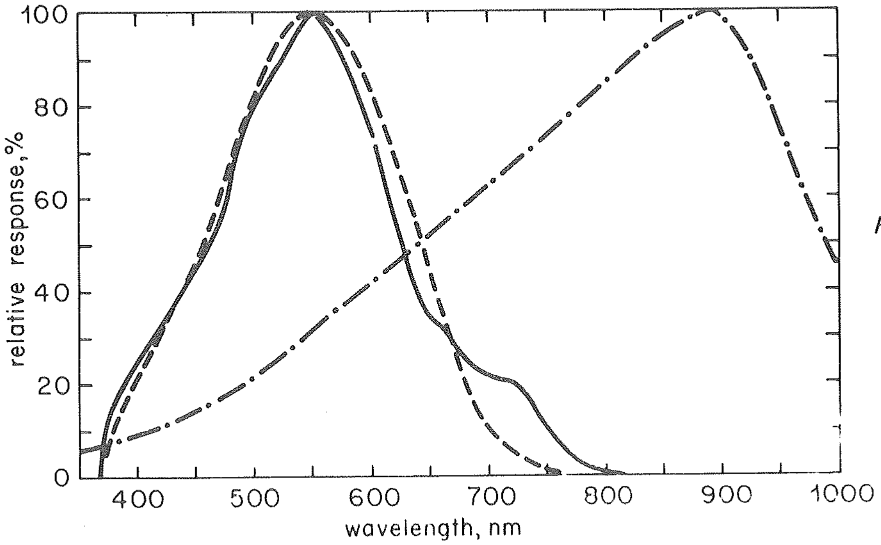


Fig. 8 - Comparison of spectral responses

——— Practical broad-band response
– – – Response used for lens testing
—·— Original photodiode response

---

* i.e. when using broad-band photoreceptor characteristics. Measurements using narrow-band characteristics were often less accurate because of poorer signal-to-noise ratio of the photoreceptor output signal.

The asymmetry ratio (p') is defined by the expression

$$p' = \frac{\text{smallest light output maximum}}{\text{greatest light output maximum}} \quad \ldots\ldots(4)$$

On the above basis asymmetry ratio values were accurate to about ±2·5% since both oscilloscope trace measurements were made near the full trace height of 4 cm.

6. Conclusions

Equipment for measuring the light-output characteristics of metal-halide discharge lamps has been constructed, embodying the following features:—

1) Provision for lamp excitation, including suitable ballasting arrangements, using sinusoidal power supply sources having a frequency range of approximately 50 Hz to 2 KHz. Alternatively, provision was also made for using non-sinusoidal lamp excitation.

2) Measurement of lamp voltage and current waveforms, from which the power dissipated in the lamp could be calculated.

3) Photoreceptor spectral response shaped to represent the overall spectral sensitivity of typical colour film stocks.

4) Use of a light chopping technique to give a reliable "zero light" reference.

It is estimated that ripple ratio values could be measured to within about ±5%.

7. References

1. TAYLOR, E.W. On the visibility of luminance fluctuations in television pictures, and exposure variations in motion picture film. BBC Research Department Report No. 1975/13.

2. TAYLOR, E.W. Some aspects of the use of metal-halide discharge lamps for film lighting. BBC Research Department Report No. 1976/2.
   2a Ibid., Appendix.

3. TAYLOR, E.W. Film lighting using metal-halide lamps: the effect of intensity ripple asymmetry. BBC Research Department Report No. 1977/8.
   3a Ibid., Section 5.3.
   3b Ibid., Section 6.5.

4. TAYLOR, E.W. Film lighting using metal-halide lamps: some operating conditions giving freedom from picture luminance fluctuations. BBC Research Department Report No. 1977/19.

5. WAYMOUTH, J.F. Electric discharge lamps. MIT Press, Cambridge, Mass., 1971.
   5a Ibid., pp 28-39 and Fig. 2.9.
   5b Ibid., Chap. 12, pp 306-335.
   5c Ibid., Fig. 12.4(b), p.312

6. BOURNE, H.K. Discharge Lamps for photography and projection. Chapman and Hall Ltd., London, 1948.
   6a Ibid., Section 7.9, p.112.
   6b Ibid., Fig. 41, p.115.

APPENDIX

Safe lamp operating techniques

The effect of the intensity ripple component in producing exposure variations has been discussed in detail elsewhere.[2] This effect is at its greatest when the exposure interval (the time during which film is exposed to the scene illumination) contains approximately one-half of a cycle of the ripple waveform in addition to a whole number of such cycles. Furthermore, the permissible amount of exposure variation, for the resulting fluctuations in picture luminance to remain imperceptible, varies with the frequency of these luminance fluctuations, being smallest when this frequency is equal to or greater than seven Hertz. If, therefore, the amount of exposure variation is less than this smallest value even when the effect of the intensity ripple in producing such exposure variations is at its greatest (as described above), picture luminance fluctuations will not be perceptible, irrespective of the relationship between the exposure interval and the ripple waveform. Under such conditions a metal-halide discharge lamp can be used safely* for film lighting without taking account of any relationships between lamp supply frequency, camera shutter angle and camera frame frequency.

Relationships between ripple ratio value (see Equation 3, Section 5) and lamp supply frequency which govern the existence of such safe lamp operating techniques have been derived[2a] on the assumption that the ripple waveform may be considered as being sinusoidal, and a diagram (Ref. 2a, Fig. 14) has been prepared showing a contour delimiting the region of safe lamp operation. As these relationships also involve the camera shutter angle and frame frequency, the above-mentioned diagram has proved rather inconvenient as a method of determining the condition of safe lamp operation for practical lamp and camera parameters. The construction of an alternative diagram, which provides a more direct indication of safe lamp operating conditions, is discussed below.

The derivation of the "safe lamp operating technique" diagram (appreviated to the acronym SLOT diagram in the following discussion) is based on two relationships involving the number (n) of complete cycles of ripple waveform included in the exposure interval. On the one hand, the value of ripple ratio (p_{min}) that will give an amount of exposure variation equal to the smallest permissible value when there are (n + ½) cycles of ripple waveform included in the exposure interval may be obtained by re-arranging Equation 41a of Ref. 2a. This leads to the relationship

$$p_{\mathrm{min}} = \frac{2(159{\cdot}2 - n) - 1}{2(159{\cdot}2 + n) + 1} \qquad \ldots\ldots(5)$$

On the other hand, expressing a length of exposure interval equal to (n + ½) cycles of ripple waveform in terms of ripple period, camera frame period and camera shutter angle, and then re-arranging the expression in terms of frequencies rather than periods, leads to the relationship

$$f_s = \frac{180}{\theta} f_c \ (n + ½) \qquad \ldots\ldots(6)$$

where f_s is the lamp supply frequency
f_c is the camera frame frequency
and θ is the camera shutter angle in degrees

(Note that this is similar to Equation 42 of Ref. 2a except that the "extra" half-cycle of ripple waveform has been included in the present case). It can therefore be seen that Equations 5 and 6 define, for given common values of n, a set of pairs of values of ripple ratio and lamp supply frequency. The locus of these values, when plotted (Fig. 10), defines the contour bounding the region of safe lamp operation. Fig. 10 therefore represents a SLOT diagram as described above. If the measured relationship between ripple ratio and lamp supply frequency, obtained as described in the body of this Report, is also plotted on the SLOT diagram (dotted line in Fig. 10), the intersection of this curve with the contour bounding the region of safe lamp operation indicates the minimum lamp supply frequency for which safe lamp operation is possible. In fact, a separate contour is required for differing values of shutter angle and camera frame frequency, and the minimum safe lamp supply frequency is therefore dependent

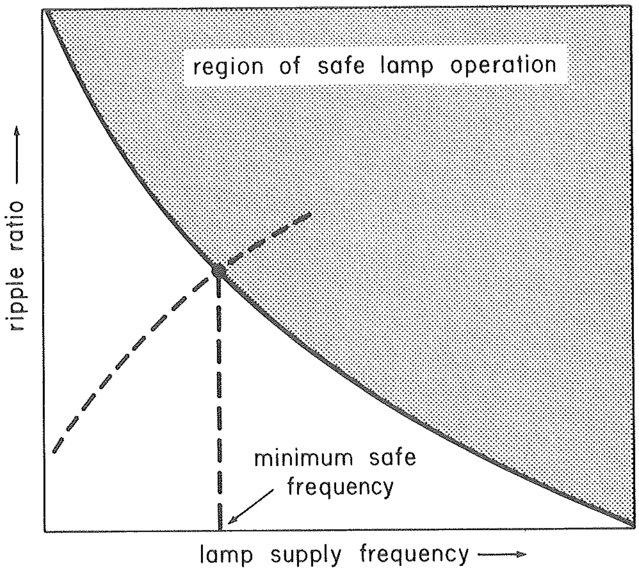


Fig. 10 - Illustration of SLOT diagram

—— Contour bounding region of safe operation
– – – Characteristics of practical lamp

---

* i.e. in respect of freedom from significant exposure variations. "Safety" in the context of "absence of hazard" is not the concern of this Report.

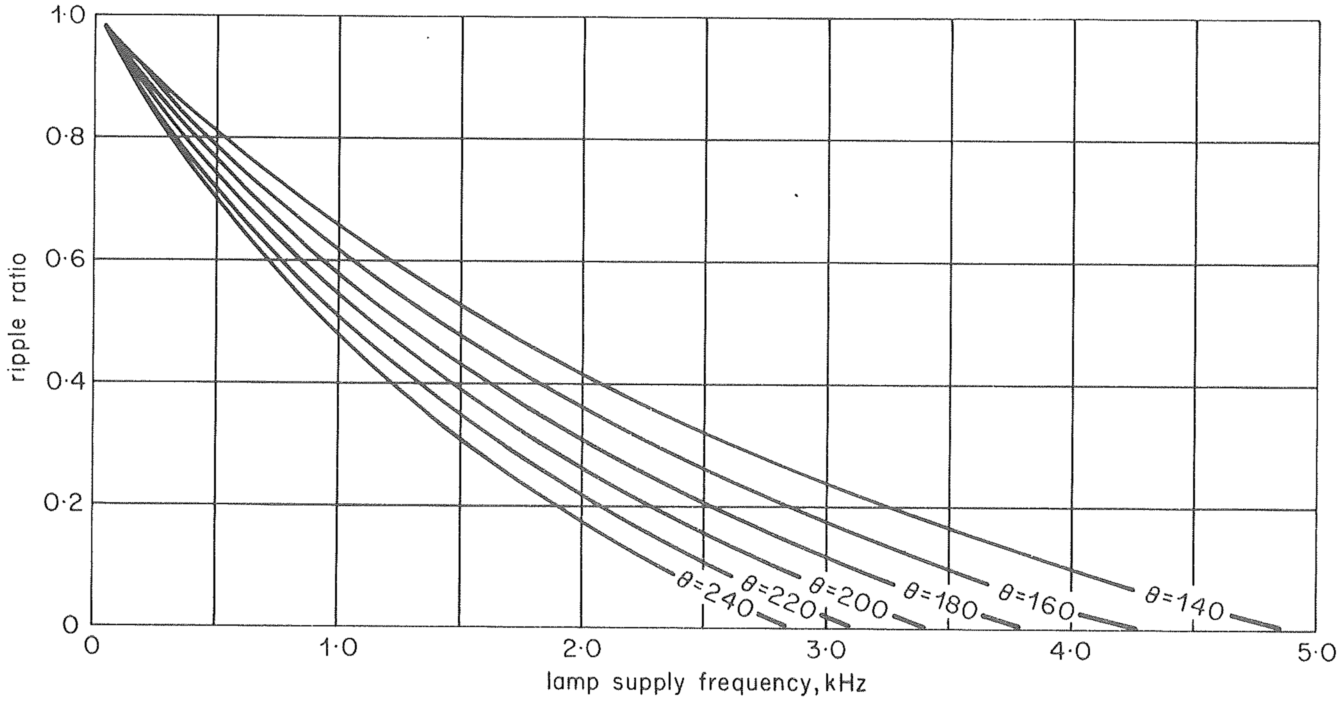


Fig. 11 - Safe lamp operating technique (SLOT) diagram for camera frame frequency of 24 Hz

Shutter angle (θ) values are in degrees

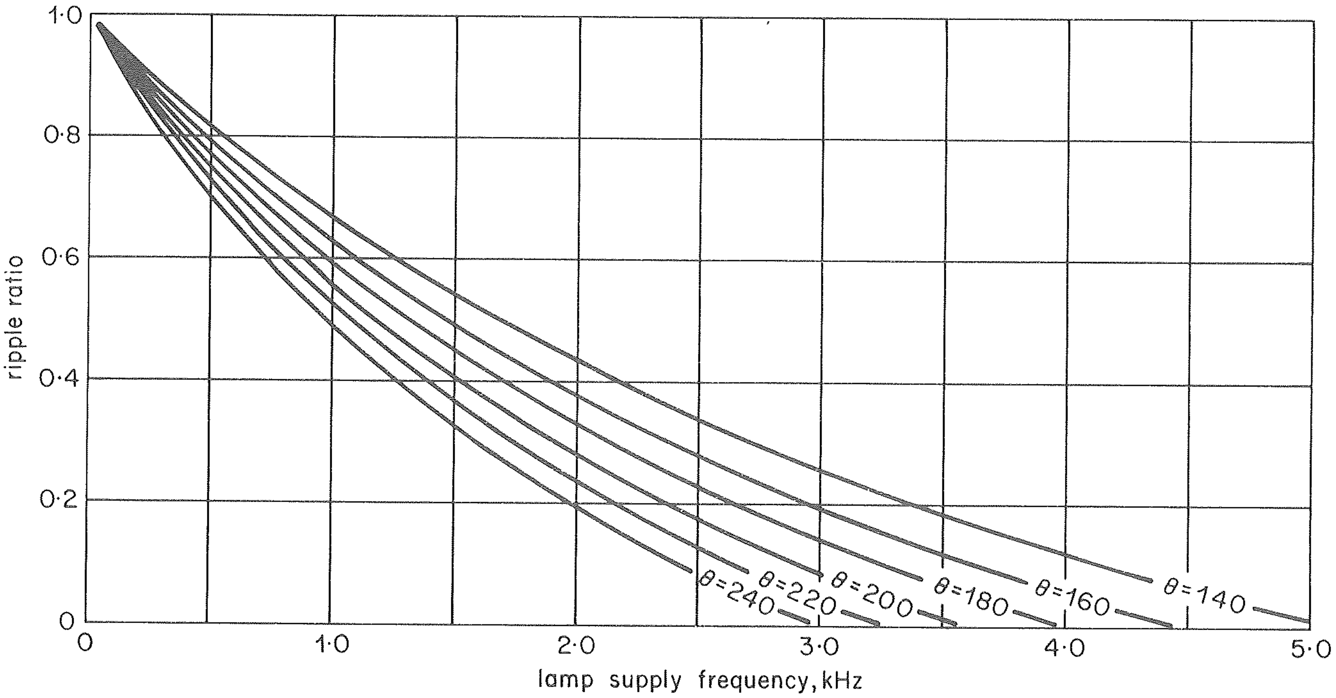


Fig. 12 - Safe lamp operating technique (SLOT) diagram for camera frame frequency of 25 Hz

Shutter angle (θ) values are in degrees

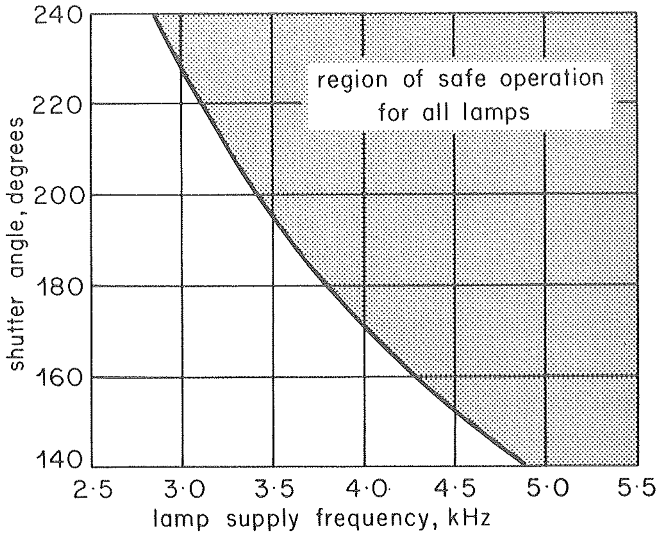


Fig. 13 - Safe operating conditions for all lamps: camera frame frequency 24 Hz

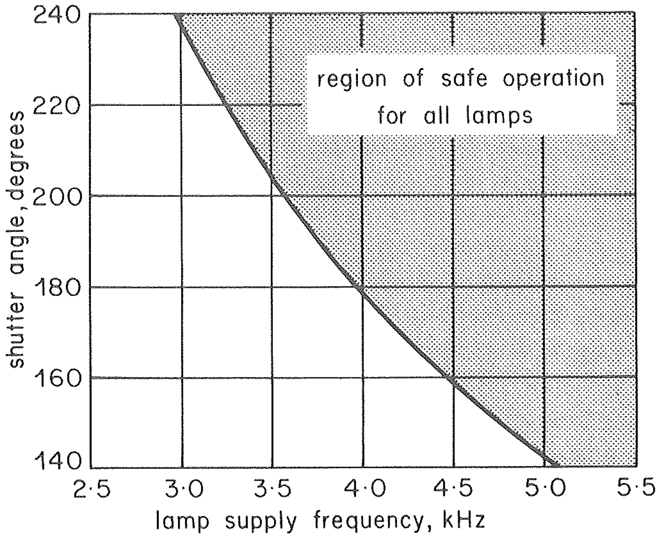


Fig. 14 - Safe operating conditions for all lamps: camera frame frequency 25 Hz

on these parameters.

In practice it may be found that metal-halide discharge lamps have an upper supply frequency limit set by stability of the discharge. In some lamps, especially those of higher power, this upper limit may be below the value required for safe lamp operation. For these lamps the safe operating technique is not feasible and account must always be taken of the relationship between camera and lamp parameters.

Figs. 11 and 12 show prototype SLOT diagrams for camera frame frequencies of 24 Hz and 25 Hz respectively, each diagram carrying contours for a range of shutter angles. Interpolation between these contours may be necessary to accommodate practical shutter angles. Figs. 13 and 14 show corresponding relationships between shutter angle and the lamp supply frequency for which safe operating conditions are obtained even if the ripple ratio is equal to zero (i.e. the intersection of the SLOT diagram contours with the supply frequency axis). Operating conditions corresponding to points above the curves in Figs. 13 or 14 are safe for all lamps (provided that the ripple waveform may still be considered as being sinusoidal): for example Fig. 14 shows that, for a camera frame frequency of 25 Hz, and a shutter angle of 180°, a supply frequency greater than 3·95 KHz will (with the above proviso) give safe operation for all lamps. This does not necessarily imply, of course, that in practice all such lamps will operate with stability when supplied at this high frequency.

The effect of asymmetry of the ripple waveform, when alternate maxima of the ripple waveform differ in magnitude (see Equation 4, Section 5), may be briefly considered. The greatest effect of ripple asymmetry in producing exposure variations occurs when there is an exact odd number of complete ripple waveform cycles in the exposure interval, as the exposure interval will then contain an "extra" larger or smaller ripple cycle.[3a] For this component of exposure variation to be of negligible effect its magnitude as predicted by Equation 37 of Reference 3a must not exceed the most stringent permitted value. If this condition is satisfied when the ripple ratio value (p_{min}) is as given by a SLOT diagram contour, the effect of ripple asymmetry will be negligible. A relationship giving the minimum permissible asymmetry ratio (p'_{min}) in terms of the number of ripple cycles in the exposure interval can be derived by substituting for p_{min} from Equation 5 into Equation 37 of Reference 3a:* this procedure leads, after considerable algebraic manipulation, to the expression

$$p'_{min} = \frac{1{\cdot}4728n + 638{\cdot}1}{6{\cdot}5431n + 640{\cdot}1} \qquad \ldots\ldots(7)$$

The value of n is related to the lamp supply frequency by Equation 42 of reference 2a (as exact whole numbers of ripple waveform cycles are contained in the exposure interval the inclusion of an extra half cycle as in Equation 6 is strictly speaking incorrect). This equation and Equation 7 can therefore be used, by a method analogous to that used for obtaining the SLOT diagram (Figs. 11 and 12) to derive contours bounding the region of safe lamp operation in respect of ripple asymmetry. Fig. 15 shows such contours for shutter angles of 140° and 240° (i.e. the extreme cases shown in the SLOT diagrams) and for camera frame frequencies of 24 Hz (dotted lines) and 25 Hz (full lines). Since present experience[3b] indicates that asymmetry ratio values less than 0·9 are very unlikely to be met with in practice, it can be seen from Fig. 15 that for all practical shutter angles the effect of ripple asymmetry can be discounted when using the SLOT diagrams to find the minimum lamp supply frequency for which safe lamp operation is possible, provided that this frequency is greater than about 500 Hz.

---

* note that in this context N in Equation 37 of Reference 3a is equal to n in Equation 5.

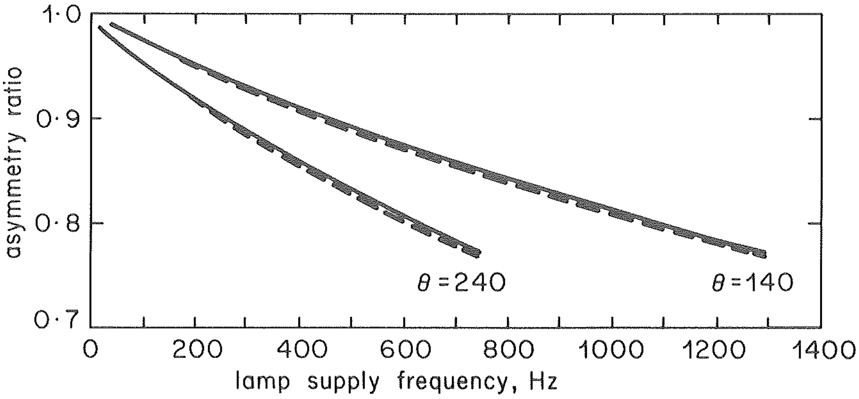


Fig. 15 - Contours of limiting asymmetry ratio

— Camera frame frequency 25 Hz

- - - Camera frame frequency 24 Hz

Shutter angle (θ) values are in degrees

HR/JUC

Printed by BBC RESEARCH DEPARTMENT, Kingswood Warren, Tadworth, Surrey, KT20 6NP